Optimization of Laminated Composite Structures Using Design Space of Lamination Parameters(積層パラメータ設計空間を利用した積層複合材構造の最適化)

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論 文 内 容 要 旨

1. Introduction

Laminated composites have been widely used in aerospace, civil, and mechanical structures because they offer better mechanical properties over traditional materials. The mechanical behavior of laminated composites is strongly dependent on their laminate configurations, i.e. layer angles and layer thicknesses. Therefore, an important topic is to optimize the laminate configurations in order to meet specific requirements for particular applications.

This thesis is concerned with the layup optimization of laminated composite structures. The laminate configurations of the laminated composite structures are expressed as layup functions, i.e. the layer angle is expressed as a function of its position through the thickness. For layup optimization, lamination parameters, i.e. functionals of the layup function, are used as design variables. The stiffnesses of the laminated composite structures are expressed as linear functions of the lamination parameters. Thus, all the laminate configurations can be taken into consideration using a small number of design variables and, for some applications, the layup optimization problem is convex, i.e. no local optima. In design space of lamination parameters, laminate configurations exist only for lamination parameters inside a convex feasible region. A mathematical formulation for the problem of determining the feasible region in general design space of lamination parameters is developed and a reliable and efficient layup optimization method with high applicability in tailoring laminated composite structures is proposed. Symmetrically laminated thick plates are optimally tailored to increase their fundamental frequencies using the design space of six lamination parameters. Buckling characteristics and layup optimization of long laminated cylindrical shells subjected to combined buckling loads of axial compression and torsion are examined using the design space of twelve lamination parameters. The design space of twelve lamination parameters is also used to examine the flexural characteristics and layup optimization of laminated plates under several hygrothermal conditions.

2. Lamination Parameters for Laminated Composites

In Chapter 2, a mathematical formulation for determining the boundary of the feasible region in general design space of lamination parameters is developed based on a variational approach. For the first-order shear deformation theory (FSDT) and for the classical lamination plate theory (CLPT), in general design space of the twelve lamination parameters $\xi^A_{1,2,3,4}, \xi^B_{1,2,3,4}$ and $\xi^D_{1,2,3,4}$, the boundary of the feasible region is obtained by determining the layup function $\theta(\bar{z})$ which maximizes the following functional:

$$F[\theta(\bar{z})] = \sum_{i=1}^{4} k_i^A \xi_i^A + \sum_{i=1}^{4} k_i^B \xi_i^B + \sum_{i=1}^{4} k_i^D \xi_i^D . \tag{1}$$

Geometrically, F is constant on a hyperplane whose unit normal is $\mathbf{k} = \{k_1^A,\ldots,k_4^A,k_1^B,\ldots,k_4^B,k_1^D,\ldots,k_4^D\}^T$ and the hyperplane is translated in the normal direction when F increases as shown in Fig. 1. The limit of the feasible region of twelve lamination parameters is reached at maximum F for given $\mathbf{k}$. Thus, due to the convexity of the feasible region, the boundary of the feasible region is determined by obtaining hyperplanes for all directions $\mathbf{k}$.

In order to clarify the matters which demand special attention using the present formulation, the feasible region for a simple design space is examined analytically. The feasible regions in different design spaces for vibration or buckling design of symmetrically laminated composites are also examined numerically as examples of practical application. New explicit expressions relating the lamination parameters are derived. The relationship among the lamination parameters on the feasible region is also discussed by comparing the obtained feasible regions. For higher order theories, new lamination parameters are introduced and the feasible region as well as the explicit expressions relating them are examined.

3. Vibration Characteristics and Layup Optimization of Symmetrically Laminated Thick Plates for Fundamental Frequencies

In Chapter 3, the layup optimization of symmetrically laminated thick plates for vibration is carried out. FSDT is used and six lamination parameters, i.e. $\xi^D_{1,2,3,4}$ and $\xi^A_{1,3}$, are adopted as design variables to tailor symmetrically laminated thick plates in order to achieve maximum fundamental frequencies. Figure 2 shows the contours of the normalized fundamental frequency $\bar{\omega}$ on ξ_1^D, ξ_2^D plane for $\xi^D_{3,4} = \xi^A_{1,3} = 0$ for a simply suported rectangular plate. The contours are shown in the region given by the known explicit expressions relating the six lamination parameters and the boundary of the feasible region is also shown by the dashed line. It can be observed that $\xi^D_{1,2}$ for maximizing $\bar{\omega}$ are outside the feasible region. Because the explicit expressions relating all the six lamination parameters are not known, we propose a general layup optimization approach which consists of four optimization steps. In the first step, the optimization is performed in a region larger than the feasible region of the lamination parameters to maximize the fundamental frequencies. In the second step, another optimization is performed to check whether the set of lamination parameters found in the first step is feasible or not. For a set of lamination parameters found infeasible, the third step is performed to maximize the fundamental frequency only on the boundary of the feasible region. The fourth step is an optimization which is performed to obtain a laminate configuration for the set of optimum lamination parameters. Mathematical programming methods are used to obtain the optimum results for different boundary

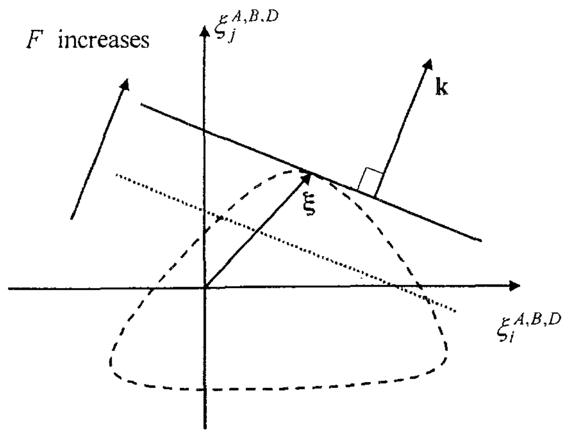

Fig. 1 Feasible region of lamination parameters

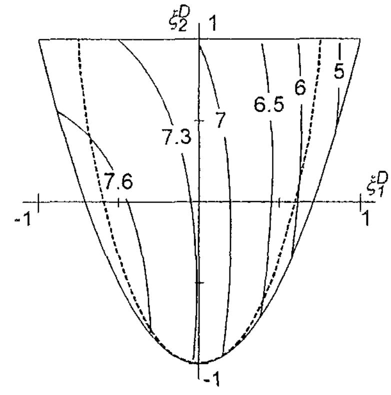

Fig. 2 Contours of $\overline{\omega}$ on ξ_1^D, ξ_2^D plane

conditions and aspect ratios of the laminated thick plates. The optimum results obtained taking into consideration the transverse shear effect in FSDT are compared with those obtained by neglecting the transverse shear effect in CLPT. For FSDT as well as for CLPT the optimum laminate configurations have the characteristics of special orthotropic laminates without bending-twisting coupling. However, the laminate configurations for FSDT are different from those for CLPT due to the transverse shear effect.

4. Buckling Characteristics and Layup Optimization of Long Laminated Cylindrical Shells under Combined Buckling Loads

In Chapter 4, the buckling characteristics and layup optimization of long laminated cylindrical shells under the combined loads of axial compression and torsion are examined using Flügge's theory. The buckling characteristics, i.e. buckling loads and buckling modes, are discussed in the design space of the twelve lamination parameters $\xi_{1,2,3,4}^A, \xi_{1,2,3,4}^B$ and $\xi_{1,2,3,4}^D$. The layup optimization for maximizing the buckling loads of laminated cylindrical shells is carried out using all twelve lamination parameters as design variables. Using a method similar to that developed in Chapter 3, the optimization is carried out for different combinations of axial compression and torsion, and for different sets of design variables in the design space of lamination parameters. In case (A) the cylindrical shells are allowed to have any laminate configuration, i.e. $\xi_{1,2,3,4}^A, \xi_{1,2,3,4}^B$ and $\xi_{1,2,3,4}^D$ are used for optimization, in case (B) symmetrically laminated cylindrical shells are considered, i.e. $\xi_{1,2,3,4}^A$ and $\xi_{1,2,3,4}^D$ are used for optimization while $\xi_{1,2,3,4}^B = 0$, and in case (C) the cylindrical shells are restricted to have orthotropic laminate configurations, i.e. $\xi_{1,2}^A, \xi_{1,2}^B$ and $\xi_{1,2}^D$ are used for optimization while $\xi_{3,4}^A = \xi_{3,4}^B = \xi_{3,4}^D = 0$. The maximum buckling loads $\overline{N}_x$ and $\overline{N}_{xy}$ are always obtained for case (A) as shown in Fig. 3. Note that there are three regions where Euler and/or local buckling modes are present for different combinations of buckling loads of axial compression $\overline{N}_x$ and torsion $\overline{N}_{xy}$. For the regions I and III, respectively, only the Euler buckling mode and only the local buckling modes occurs, while both Euler and local buckling modes are possible for the region II. The buckling modes change, i.e. Euler or local, depending on the laminate configurations and the loading ratio. The laminate configurations aiming to realize the optimum lamination parameters are also examined. In case of combined loads of axial compression and torsion, the optimum laminate configurations are unsymmetric.

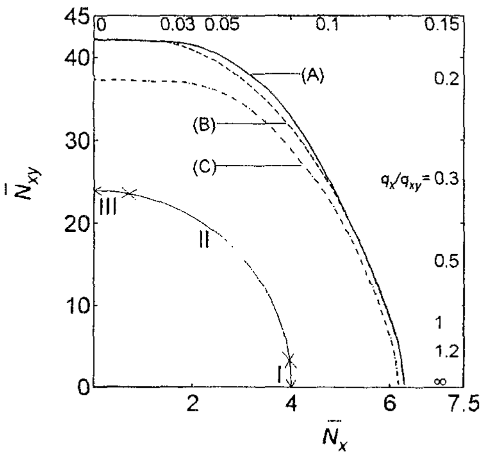

Fig. 3 Combinations of maximum buckling loads

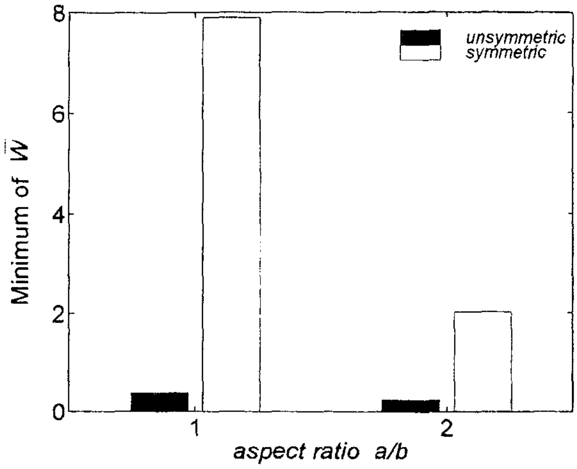

Fig. 4 Minimum of $\overline{W}$ for laminated plates

5. Flexural Characteristics and Layup Optimization of Laminated Plates under Hygrothermal Conditions

In Chapter 5, the flexural characteristics and layup optimization of laminated plates under environmental conditions of temperature and moisture, i.e. hygrothermal conditions, are examined. On the laminated plates there are no symmetry or orthotropy conditions imposed. Based on CLPT, twelve lamination parameters are introduced and all the stiffness couplings are taken into consideration in the analysis. The deflection of laminated plates is analyzed in the design space of the twelve lamination parameters. The deflection is most sensitive with respect to coupling lamination parameters. The location on the plate and the magnitude of the maximum deflection $\overline{W}$ can be controlled by the use of lamination parameters. The layup optimization for minimizing the deflection of laminated plates is carried out using all the twelve lamination parameters as design variables. The laminate configurations intending to realize the optimum lamination parameters are also examined. In hygrothermal conditions, the maximum deflection of laminated plates with in-plane hygrothermal stresses can be reduced by the use of optimized unsymmetric laminate configurations as shown in Fig. 4.

6. Conclusions

The explicit expressions which describe the feasible region in design space of all lamination parameters remain unknown. However, the boundary of the feasible region in design space of all lamination parameters was determined and new explicit expressions relating restricted numbers of lamination parameters were derived. The general layup optimization approach proposed in this thesis has been proved efficient for optimization problems involving stiffnesses from different categories and for the optimization of laminated composites without restrictions imposed on their laminate configurations. For further research in this field, attention should be paid to derive the complete set of explicit expressions relating all the lamination parameters as well as to identify and carry out layup optimization problems for which the lamination parameters are useful and efficient design variables.

論文審査結果の要旨

積層複合材は層厚及び繊維配向角に関するテーラリングによって優れた剛性特性を発揮させることができることから，近年，航空機や宇宙機の構造に多用されるようになり，統一的な効率的最適化手法の確立がきわめて重要となっている。本論文は，積層複合材構造の剛性特性最適化問題を対象に，あらゆる積層構成を考慮できる統一的な取り扱いが可能な効率的最適化手法を確立し，それを適用して得られた成果をまとめたもので，全編6章よりなる。

第1章は序論であり，本研究の背景及び目的を述べている。

第2章では，あらゆる積層構成を考慮できるパラメータとして積層パラメータを導入し，剛性マトリックスとの関係を示すとともに，変分法を基礎として積層パラメータを設計変数としたときの設計空間の許容領域の決定法を確立している。これは優れた成果である。

第3章では，一次せん断変形理論に基づいて，厚い対称積層複合材平板の振動特性について6個の積層パラメータを用いた一般的な議論を展開している。さらに，効率的最適化手法を新しく開発し，振動特性が最適となる積層構成を求め，古典積層理論に基づく結果との比較検討を行っている。これは有用な成果である。

第4章では，圧縮及び捩りの組合せ荷重を受ける長い積層複合材円筒殻の座屈特性を取り上げ，12個の積層パラメータを用いた座屈特性の一般的把握と最適化を行っている。その結果，座屈特性を最適とする積層構成は非対称となることを明らかにしている。これは重要な成果である。

第5章では，温湿環境下での積層複合材平板の曲げ特性を取り上げ，12個の積層パラメータを用いて一般的な検討を行っている。さらに，効率的最適化法を適用して曲げ特性が最適となる積層構成を求め，実用上有用な成果を得ている。

第6章は結論である。

以上要するに本論文は，積層複合材構造における各種の剛性特性最適化問題を対象に，あらゆる積層構成を考慮できる積層パラメータを利用した統一的な効率的最適化手法を確立し，それを適用して実用上重要な成果を得ており，航空宇宙工学及び機械工学の発展に寄与するところが少なくない。

よって，本論文は博士(工学)の学位論文として合格と認める。